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Procedia Engineering 132 (2015) 679 – 685

**Procedia  
Engineering**[www.elsevier.com/locate/procedia](http://www.elsevier.com/locate/procedia)

The Manufacturing Engineering Society International Conference, MESIC 2015

## Experimental study of surface finish during electro-discharge machining of stainless steel

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### Abstract

The main objective of this research is to show the influence of EDM parameters such as current intensity and depth of penetration on both the surface finish and process productivity, in order to deduce technical guidelines for selection of the optimum process conditions. A series of experimental tests about electro-discharge machining of AISI 316 stainless steel using copper electrodes were carried out. The surface roughness parameters were registered, and scanning electron microscopy (SEM) was applied to analyze the surface integrity, as well as the migration of electrode material elements to machined surface. The process productivity and surface finish were studied as a function of the current intensity employed during material removal and the overall depth of penetration on the workpiece material. It was proved that both current intensity and depth of penetration present a high influence on the surface integrity and production time during EDM of this stainless steel.

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Peer-review under responsibility of the Scientific Committee of MESIC 2015

**Keywords:** Electro-Discharge Machining (EDM); Experimental analysis; Surface morphology; Surface roughness; Structural steel

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### 1. Introduction

Electro-discharge machining (EDM) is one of the non-conventional machining technologies with a greater presence in the industry, due to the possibility of generating parts of high geometric complexity and constituted by

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hard to machine materials. In order to determine the optimum conditions for EDM, the electrical process conditions, dielectric properties and thermal energy supply must be studied by both experimental and numerical methods.

Numerous studies about the influence of process parameters and fluid dielectric on EDM performance [1-6], the estimation of energy distribution and crater diameter [7-8], the characteristics of plasma channel and the effect of bubbles and debris on successive discharges [9-10], new techniques for a better control of EDM process [11], and other applications such as wire EDM, EDM drilling and combination with other manufacturing techniques [5-6, 12] were developed during the recent years. Nevertheless, in spite of these previous studies, new research efforts are needed to clarify the influence of the different factors involved in this process [2].

M. Hourmand et al. [1] analysed the electro-discharge machining of metalmatrix composites (MMCs) using an oil-based dielectric fluid with aluminum powder. The material removal rate (MRR) was proved to depend specially on the burning voltage, intensity current, two-level interaction between voltage and current, two-level interaction between current and pulse time and second-order effect of burning voltage, while the electrode wear ratio (EWR) was mostly affected by the pulse time and second-order effect of this parameter. In the work of A.K. Singh et al. [2], the surface texture of Superco 605 superalloy after electro-discharge machining was studied, considering the effect of some electrical process parameters and the addition of graphite powder to the dielectric fluid. The powder-mixed dielectric allowed the drastic reduction of surface irregularities of machined part, while the current polarity, peak current and pulse time also presented a great relevance for surface finish.

Y. Zhang et al. [3] carried out the analysis of material removal in electro-discharge machining using five different dielectrics, which include gaseous dielectrics such as air and oxygen, and liquid dielectrics such as de-ionized water, kerosene and water-in-oil (W/O) emulsion. From the results of this work, the pressure above the discharge point was identified as a crucial factor for material removal. W. Wang et al. [4] analysed the effect of dielectric fluid on the performance of EDM process for machining of titanium alloys, considering three alternatives such as a compound dielectric, distilled water and kerosene. The material removal rate is maximized when using the compound dielectric, while the lowest electrode wear ratio is obtained with kerosene and the optimum surface finish corresponds to distilled water.

The work of S. Plaza et al. [5] was focused on electro-discharge machining of micro-holes with high aspect-ratio in Ti6Al4V alloys. The effect of EDM parameters on material removal rate, electrode wear, machining time and micro-hole quality was evaluated, and the application of helical-shaped electrodes was proposed to facilitate the evacuation of debris for high hole depths. L. Li et al. [6] investigated the removal efficiency, surface roughness, surface alloying and microhardness during the wire EDM of Inconel 718 nickel-based alloys. Three different trim cut (TC) modes were examined, and the preferable TC modes about surface finish, absence of microcracks and microhardness were deduced.

The analysis of the characteristics of plasma channel and thermal energy distribution on the machining zone is of great importance for electro-discharge machining, due to their high influence on the resultant properties of machined parts. Y. Zhang et al. [7] determined the thermal gradients using a thermo-physical model based on the finite element method (FEM), and deduced the energy distribution and plasma diameter by the comparison between the melted material contours obtained by numerical prediction and experimental measurement. Different dielectric fluids and current polarities were considered, and the proposed methodology was found applicable for calculation of energy distribution and plasma diameter. T. Kitamura and M. Kunieda [8] studied the diameter of heat source by single discharge EDM processes, using transparent electrodes constituted by single crystals of SiC and Ga<sub>2</sub>O<sub>3</sub>. The measured diameter of heat source was smaller than the diameter of plasma channel, and greater than the crater diameter.

M. Zhang et al. [9] revealed the differences between electro-arc machining (EAM) and electro-discharge machining (EDM) processes, including the characteristics of plasma channel and crater geometry. The current intensity and pulse time determined the diameter and temperature of plasma channel, and also the geometry of craters generated during the machining process. T. Kitamura et al. [10] was focused on the study of bubbles on the gap between the workpiece and electrode. Transparent electrodes were employed to visualize the gap, and it was proved that the bubbles generated by each spark covered more than the 70% of working surface during some hundreds of discharges.

The objective of this work is to determine the effect of some of the main process parameters of electro-discharge machining, in terms of both the surface finish and process productivity. Among the different factors involved in EDM process, the present study is oriented to the analysis of current intensity and depth of penetration, as some of the process parameters with a greater effect on material removal by electro-discharge machining. From the experimental results obtained in this work, it is deduced technical guidelines that can be applied to select the optimum process conditions for this workpiece material.

## 2. Experimental procedure

In this work, two different parameters of EDM process are considered, such as the current intensity applied during material removal and the total depth of penetration on the workpiece material. The values assumed for current intensity during the EDM experiments were from 6 and 14 A, while penetration depth was varied from 3 to 7 mm. The depth of penetration was considered in order to describe the effect of surface heating during a greater time and electrode wear. The rest of process parameters were retained constant during the totality of these tests, including a burning voltage of +200 V, pulse time of 100  $\mu$ s and pause time of 25  $\mu$ s.

The EDM experiments were carried out using an ONA DATIC D2030 machine tool with a numerical control DATIC F30. The workpiece material was 40x40x10 mm plates of AISI 316 stainless steel, and they were always located at the same position with the help of an auxiliary positioning tool that was previously fixed to the EDM machine working table.

This experimental study was made with copper electrodes, and a new electrode surface was mounted in the machine tool for each EDM test. The copper electrodes were machined until a same surface finish before each cutting experiment, and so the same conditions were maintained in the cutting tool active surface at the beginning of all the EDM tests.

The measuring of surface roughness in machined samples was executed by a profilometer Hommelwerke T1000, and a scanning electron microscope Hitachi S-3500N was applied to analyse the texture of the final surface of workpiece material. Not only the surface finish but also the overall machining time was registered, in order to know the achievable productivity in the EDM process.

## 3. Discussion of results

In the electro-discharge machining tests of this study, different values of current intensity and total penetration depth were adopted, and their influence on both the surface finish obtained in machined parts and the production time required to complete the material removal process was evaluated. The measuring of surface finish was made in the central zone of machined surfaces, in order to avoid the possible differences in thermal heating or debris cleaning over the surface borders.

The surface finish of machined samples was described by the maximum height of the profile ( $R_t$ ) and arithmetic average roughness ( $R_a$ ), and the root mean squared roughness ( $R_q$ ) was also registered. The surface finish of machined parts was also examined by scanning electron microscopy (SEM), and the values obtained for these roughness parameters were compared to the texture depicted in the SEM images.

Figs. 1 to 2 illustrate the effect of current intensity on the surface roughness of machined parts for the cutting conditions considered in this study. These figures show the surface roughness that corresponds to a penetration depth of 3 and 5 mm, respectively. Figs. 1a and 2a represent the results obtained for the maximum height of the profile ( $R_t$ ), while the arithmetic and quadratic average roughness parameters ( $R_a$  and  $R_q$ ) are depicted in Figs. 1b and 2b.

According to these figures, the arithmetic average roughness and root mean squared roughness describe a tendency similar to the maximum height of the profile. These three roughness parameters present a good adjustment to a linear relation as a function of current intensity, with a worse surface finish for the higher values of current intensity.

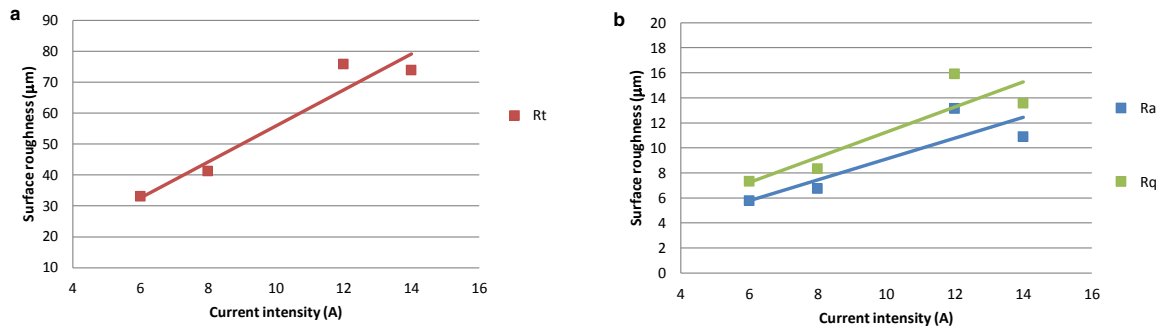


Fig. 1. Surface finish as a function of current intensity (for EDM tests with penetration depth of 3 mm).

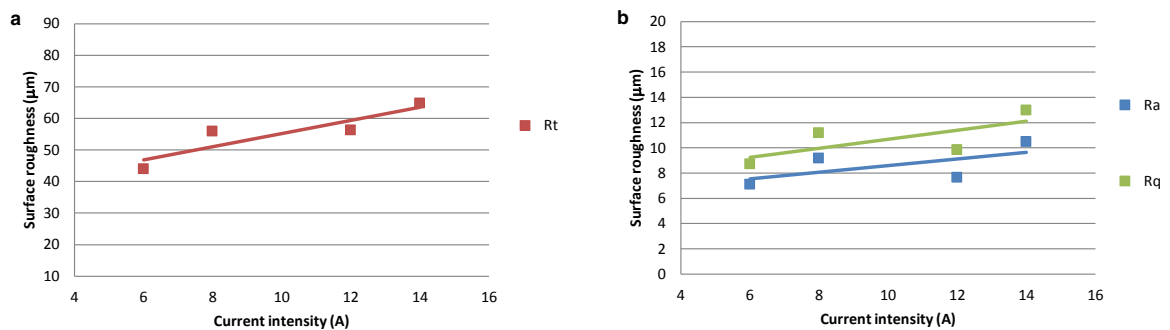


Fig. 2. Surface finish as a function of current intensity (for EDM tests with penetration depth of 5 mm).

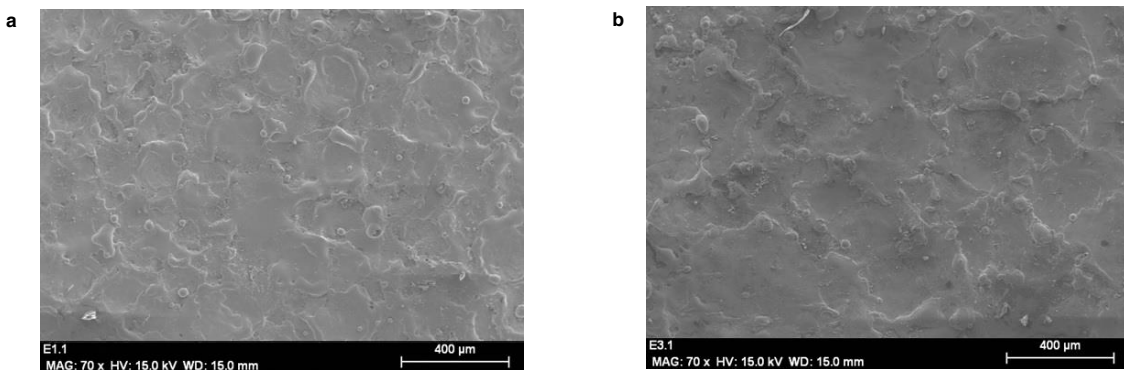


Fig. 3. SEM images of machined surface for current intensity of 6 and 12 A (for EDM tests with penetration depth of 5 mm).

A greater increase is evidenced in these surface roughness parameters for a penetration depth of 3 mm, while a more moderate increment is produced for a higher penetration depth. This can be attributed to the effect of tool degradation during the electro-discharge machining, because a higher wear was proved at the electrode active surface as a function of penetration depth, caused by the additional time that the electrode is exposed to the action of sparks and the increased troubles for debris cleaning at greater distances from the external workpiece surface.

These results can be validated by checking the appearance of machined surfaces with the help of scanning electron microscopy (SEM) techniques. The surface texture observed by SEM for increasing values of current intensity are depicted in Fig. 3.

The SEM images illustrated in this figure correspond to EDM tests with a penetration depth of 5 mm. A gradual increase is evidenced in the size of craters provoked by the sparks as a function of the current intensity applied during material removal. A good agreement is found between the topography revealed by scanning electron microscopy and the surface profiles obtained during the measuring of surface roughness.

The size of craters that were obtained in the workpiece samples subjected to electro-discharge machining with a penetration depth of 5 mm is represented in Fig. 4 in terms of crater diameter. This figure illustrates the increasing linear tendency that the crater diameter exhibits, which is in accordance to the variation of roughness parameters as a function of current intensity.

The crater diameter is proved to serve as a good indicator to describe the action of sparks during the electro-discharge machining of workpiece material considered in this study. It does not account the effect of protuberances formed on the machined surface by re-solidification of a certain portion of this metallic alloy that was previously molten. The differences between the curves representing the size of craters and the surface roughness could be attributed to the protuberances that are usually encountered on the parts generated by EDM.

The influence of process parameters on the overall time required to execute the EDM process on the workpiece samples is also studied in this work. Fig. 5 depicts the variation of machining time from the different values of penetration depth and current intensity that was assumed for the electro-discharge machining experiments, including the total duration of the EDM process according to the CNC program in which the cutting conditions and electrode displacement are defined.

As can be observed in this figure, a linear relation between the machining time and penetration depth is only found for elevated values of current intensity, meanwhile a certain quadratic tendency is evidenced for a current intensity from 6 to 8 A, with a greater increment in the overall production time as the penetration depth is increased. This quadratic increment of machining time for low values of current intensity can be due to the additional time imposed by the servo of EDM machine to conveniently extract the removed material by means of the dielectric fluid flow, when reduced material removal rates are considered.

The results shown in this figure could be considered to optimize the process productivity by selecting the recommended value of current intensity for the successive rough machining operations, after an appropriate balance between the total time that can be saved during material removal and the overwork needed to eliminate the surface irregularities provoked by previous operations with an elevated current intensity.

#### 4. Conclusions

In this work, the influence of some EDM process parameters on the surface finish of machined parts and the overall production time is studied. The surface roughness of parts generated by electro-discharge machining was measured by means of a profilometer, and scanning electron microscopy was employed to analyse the surface topography. The variation of surface finish as a consequence of current intensity and penetration depth was discussed. A linear increase in both the surface roughness and crater diameter as a function of current intensity was encountered, with a lower dependency on this parameter when elevated values of penetration depth are assumed. The effect of current intensity and penetration depth on the EDM process productivity was also evaluated, and a quadratic relation between the machining time and penetration depth was found for the lowest values of current intensity.

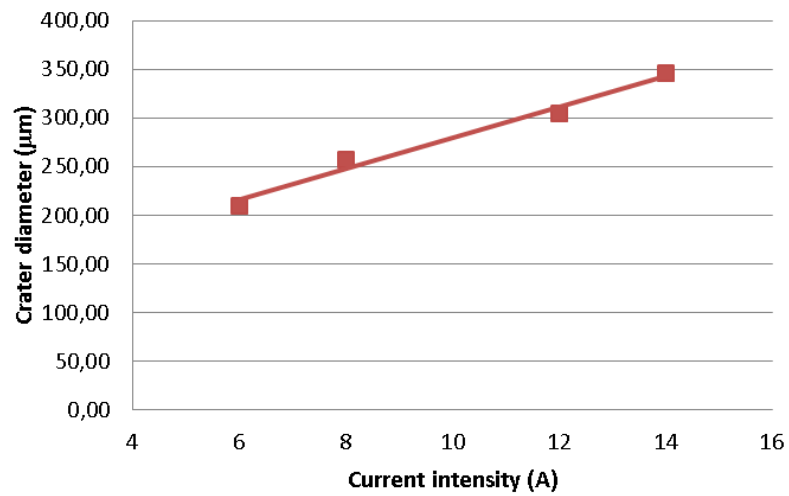


Fig. 4. Crater size as a function of current intensity (for EDM tests with penetration depth of 5 mm).

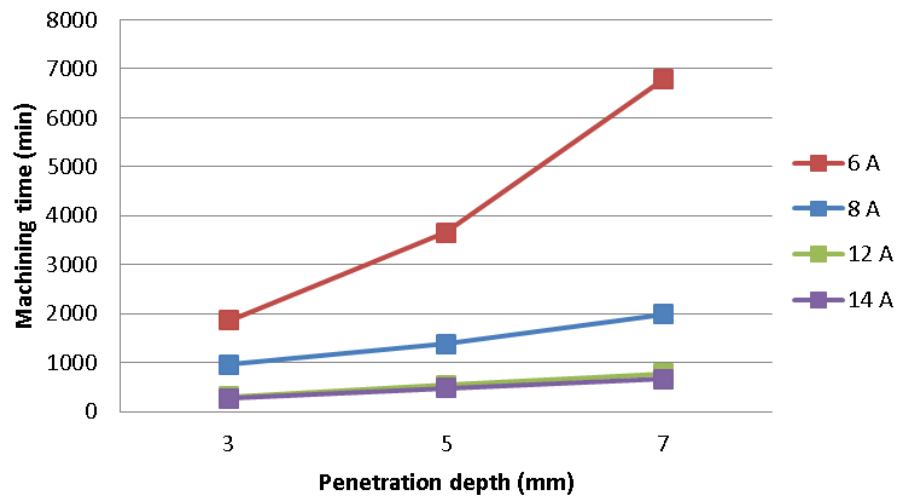


Fig. 5. Machining time as a function of penetration depth.

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